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Determination of annual and seasonal daytime and nighttime trends of MODIS LST over Greece - climate change implications

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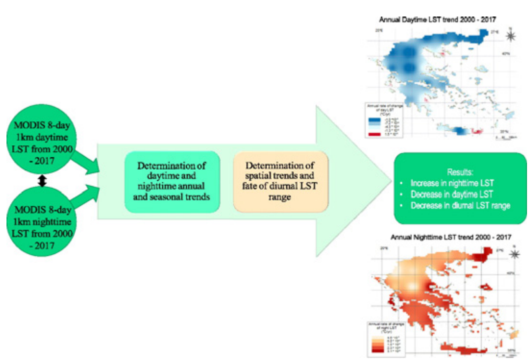
HIGHLIGHTS

- Daytime and nighttime MODIS LST data all over Greece were obtained for 2000–2017.
- Annual and seasonal trends of daytime and nighttime LST were computed.
- Spatial trends were also highlighted.
- Diurnal LST range trends were also evaluated on an annual and seasonal basis.
- Climate change is expressed as increase in LST_{min} and decrease in diurnal range.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change is one of the most challenging research topics during the last few decades, as temperature rise has already posed a significant impact on the earth's functions thus affecting all life of the planet. Land Surface Temperature (LST) is identified as a key variable in environmental and climate studies. The present study investigates the distribution of daytime and nighttime LST trends over Greece, a country in the Mediterranean area which is identified as one of the main "hot-spots" of climate change projections. Remotely sensed LST data were obtained from MODerate Resolution Imaging Spectroradiometer (MODIS) sensor in the form of 8-day composites of day and night values at a resolution of 1 km for a 17-year period, i.e. from 2000 to 2017. Spatial aggregates of 10 km × 10 km were computed and the annual and seasonal temporal trends were determined for each one of those sub-areas. Results showed that annual trends of daily LST in the majority of areas demonstrated decrease ranging from $-1 * 10^{-2}$ °C to $-1.3 * 10^{-3}$ °C, with some sporadic parts showing a slight increase. A totally different outcome is observed in the fate of night LST, with all areas over Greece demonstrating increasing annual trends ranging from $4.6 * 10^{-5}$ °C to $3.1 * 10^{-3}$ °C, with highest values in the South-East parts of the country. Seasonal trends in day and night LST showed the same pattern, i.e., a general decrease in the day LST and a definite increase in night. An interesting finding is the increase in winter LST trends observed both for day and night LST, indicating that the absolute minimum annual LST observed during winter in Greece increases. Our results also indicate that the annual diurnal LST range is decreasing.

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1. Introduction

According to the most recent Intergovernmental Panel on Climate Change (IPCC) report (IPCC, 2014) greenhouse gases (GHG) are the highest in history and climate changes are already evident in a wide variety of natural systems. These impacts are clearly attributed to human activities, while the most prominent and indisputable change is global warming with the consequent diminishing of snow and ice and sea level rise.

Besides the increased concentration of atmospheric CO_2 and the consequent temperature rise of 0.7–0.8 °C in comparison to the pre-industrial period (European Environmental Agency, 2010), there are several environmental factors that are affected by climate change. Some indicative factors are the changes in the duration, aerial extent and frequency of droughts (Di Matteo et al., 2017) and the various shifts in precipitation magnitude and its seasonal distribution (Easterling et al., 2000). Climate change prediction models give clear indications of more frequent and higher intensity phenomena such as heat waves, storm surges, warmer days with a corresponding reduction in cold days during the year, as a result of increased GHG emissions in the atmosphere (IPCC, 2014). Climate projections have suggested that global temperature may rise up to 1.8–4.0 °C until the end of the century, if measures to limit global GHG fail to control their emissions (European Environmental Agency, 2010).

The Mediterranean is characterized as one of the main "hot-spots" as indicated by climate change projections (Giorgi, 2006). Based on the most advanced sets of climate model simulations a substantial drying and warming of the Mediterranean region, especially in the warm season up to the end of the present century is predicted (Giorgi and Lionello, 2008). Such decrease in rainfall, combined with the increased temperature, is likely to affect crops as the rainy season is expected to shorten (Pnevmatikos and Katsoulis, 2006) with a consequent reduction in soil moisture available for plant growth and an increase of evapotranspiration. A reduction in the productivity of cereal crops in the Mediterranean region has already been detected (Olesen and Bindi, 2002), which also contributed to the emergence of economic difficulties that need to be confronted, since a large part of the revenues of those countries is based on the primary sector of economy (Balint et al., 2017). Concerning forests, it has been observed that they demonstrate a natural adaptability to changing climate conditions. Nevertheless, their growth and sustainability may be affected by continual fluctuations in the frequency and duration of rainfall as well as shifts in temperature. In the Mediterranean particularly, temperature rise is expected to result in a decrease in forest growth, which in combination to the projected increased frequency and intensity of fires may potentially affect wood production and the related ecosystem functions (European Environment Agency, 2010). As a result scientists have recognized the need for acquiring time series data for the identification of climate change in the Mediterranean region (Abboud-Abi Saab et al., 2004).

Modern science has introduced new ways of acquisition, evaluation and analysis of environmental data. Nowadays, monitoring can be conducted by using satellite observations, that offer a wide range of parameters for each environmental indicator (Neteler, 2010). Remote sensing has become an increasingly important source of information for climate change research. Monitoring networks have been providing in situ observations at high resolution in many parts of the world. There are still however sparsely monitored areas, where remotely sensed data constitute the only source of information (Alsdorf et al., 2007; Sun, 2013). Sun (2013) indicates the decline of water resources monitoring networks and the increased dependency on remotely sensed information for water resources assessment. Recent works using remotely sensed land surface temperature observations have demonstrated the wide range of environmental applications of those data sets, e.g. for the determination of soil moisture (Fang and Lakshmi, 2014), evapotranspiration computations (Mu et al., 2011), land use and climate change assessments (Hereher, 2017; Zhang et al., 2017), among others. Zhang et al. (2017) showed that urbanization results in LST increase which affects the environmental equilibrium. Rising temperatures have been observed both in land and ocean. Gleckler et al. (2016) found that in recent decades oceans continued warming and that the warming signal is reaching deeper in the ocean. Pal and Ziaul (2016) indicated that deforestation for extending the urban and industrial areas causes LST rise during all seasons. Other anthropogenic activities, like the creation of new agricultural territories by drying existing lakes, substantially affect the regional LST in Mediterranean countries like Egypt (Hereher, 2017). The anthropogenic warming signature is thus evident and it is safe to assume that future human activities may cause various environmental hazards, especially when future GHG emissions and global temperature exceeds the desirable limits (IPCC, 2014). It is therefore of primary importance to detect any changes related to temporal and aerial distribution of surface temperature.

Surface temperature is a vague term and may refer to skin temperature (or radiometric surface temperature), surface air temperature (or air temperature at shelter height) and aerodynamic temperature (or the temperature at the height of roughness length for heat) (Jin and Dickinson, 2010). Aerodynamic temperature cannot be measured directly and it is commonly linked to LST (Chehbouni et al., 1996). Therefore, climate assessments are based on either air temperature or LST. The term Land Surface Temperature refers to the radiative skin temperature at land surface and can be perceived as the heat feeling to the touch in a particular location on Earth's surface. Although LST differs from air temperature in its physical meaning and means of measurement, it is correlated to air temperature but can be different based on land cover or sky conditions. LST is most times 2–6 K higher than the aerodynamic temperature at daytime and lower than the aerodynamic temperature at nighttime (Jin and Dickinson, 2010). Air temperature is typically measured 1.5 m above the ground level with sensors protected from radiation and adequately ventilated (Mildrexler et al., 2011). LST can be measured either using earth based methods, i.e. hand-held radiation thermometer or by satellite or aircraft-based sensor technologies measuring thermal radiance from land surface (Jin and Dickinson, 2010). LST is derived from satellite observations over large areas using the thermal infrared (TIR) spectral channels, after removing atmospheric attenuation effects.

The present study aims at investigating the annual and seasonal trends of nighttime and daytime LST over Greece during the last 17 years. Data were acquired from the MODIS sensors on board Aqua and Terra satellites. Data were analyzed in both annual and seasonal trends, as well as in spatial context and were evaluated taking into account various land uses in Greece. Results showed that remotely sensed LST data may well reveal trends in surface temperature and highlight areas where land uses have altered the LST regime. Climate change implications were expressed as increases in minimum LST and changes in diurnal LST ranges.

2. Data and methods

2.1. Aqua/terra MODIS sensor and LST data

MODIS is a key instrument onboard Terra and Aqua satellites which are part of the NASA's Earth Observing System. Both satellites are at sun-synchronous, near-polar circular orbit. Terra passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon (https://modis.gsfc.nasa.gov/about/, accessed 10/08/2017). Terra MODIS and Aqua MODIS scan the entire Earth every 1 to 2 days, obtaining data in 36 visible/infrared bands. MODIS products have been widely used as they cover a wide spectrum of land variables, including land cover classification, vegetation indices such as Normalized Difference Vegetation Index (NDVI) and Leaf Area Index (LAI), hydrological variables such as evapotranspiration and climate variables such as LST and emissivity. Their quality is comprehensively validated and the algorithms to derive MODIS products are

widely evaluated and well documented (Fang and Lakshmi, 2014; Justice et al., 2002). A total of 44 daily 1 km spatial resolution land products are available (Fang and Lakshmi, 2014).

MODIS standard LST and emissivity products comprise one swath (Level 2) and six gridded products (Level 3). Their development is based on two algorithms. The first one known as generalized split window (GSW) is a view-angle dependent split-window LST method that uses predefined land classification model to estimate land surface emissivity (Wan and Dozier, 1996). MOD11_L2 and MOD11A1/2 products are developed with the GSW algorithm at 1 km resolution. The second one known as day/night algorithm uses the GSW method but land surface emissivity is acquired from MODIS thermal bands (Wan and Li, 1997). Products from day/night algorithm are generated at 5.6 km resolution. The MODIS LST data accuracy was assessed over a widely distributed set of locations, land cover types and time periods, via several ground-truth and validation efforts and it was found to range from 1 K to 1.5 K (Hulley et al., 2012). The largest uncertainties are found in rock and sands land cover types mostly found in dry, arid regions (Hulley et al., 2012). Other validation efforts in multiple validation sites in relatively wide ranges of surface and atmospheric conditions reported the accuracy of MODIS LST to be better than 1 °C in the range from −10 to 50 °C (Wan et al., 2004). Coll et al. (2009) conducted a validation experiment for MODIS LST in two sites, i.e. one in Valencia, Spain, and one in the Hainich forest in Germany. They used in situ LST measurements (T-based method) and an alternative method, i.e. the R-based method, using locally measured radiosonde profiles. In that work authors highlighted the issue of little available ground based data which are dedicated to specific sites only and the difficulties in scaling up from the ground point level of LST measurements to MODIS 1km^2 pixel. Results in that work showed the high accuracy and precision of the MODIS LST product, yielding LST errors with small biases and Root Mean Square Error = ±0.6 K for the two sites examined.

In our work we used MODIS LST, to estimate spatial, temporal and seasonal trends in daytime and nighttime surface temperature over mainland of Greece and in most of its islands during 2000 to 2017. The collection 5 of MOD11A2 Level 3 LST and Emissivity 8-day product used herein provides averages of the daily 1-kilometer LST product (MOD11A2) of clear sky LSTs during an 8-day period. Particularly for Greece, day LST view time is around 13.00 at noon and the night view time around 01.00 after midnight, corresponding to the pair of day and night view time of MODIS observations. Further details related to MODIS LST products can be retrieved from the user's guide found in the following URL: https://icess.eri.ucsb.edu/modis/LstUsrGuide/MODIS_LST_products_Users_guide_C5.pdf.

2.2. Spatial and temporal analysis

A specially developed R code was used for further processing the above data set. More specifically, only pixels of the highest quality i.e. cloud free and error free pixels, as reported by the quality control flags of data, were selected for further processing. This process led to a considerable reduction of available data especially during winter mainly in the high altitudes due to cloud cover. Therefore, to overcome this constraint, spatial aggregates of 10 km × 10 km were computed as averages of the 1 km × 1 km values. Upscaling the spatial range of the MODIS observations allows for increasing number of data points for further processing and has been previously reported to pose no significant change in data statistics (Bosilovich, 2006).

For each such sub-area the daytime and nighttime annual and seasonal trends were determined in the form of Least Square line fitting. Statistical significance of the trends was estimated for each of those areas by their *p*-values. Results were considered statistically significant when $p < 0.05$. In areas where p was found to be >0.05 ($p > 0.05$), it was assumed that there was virtually no trend in the corresponding time series. Those areas corresponded to <1% of the study area and only for winter they amounted to 1.2% of the total examined area. Grid files with the estimated slope values of annual and seasonal daytime and nighttime trends were produced and the associated maps were prepared using QGIS software. All MODIS LST data are freely available from the NASA and USGS Land Processes Distributed Active Archive Center (LP DAAC) (https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod11a2), and the R (https://www.r-project.org/) and QGIS (www.qgis.org) programs used for processing, are both provided free as well.

2.3. Study area description

Greece is a typical Mediterranean country, with a diverse topography which also influences its climate to a great extent. The climate is predominantly Mediterranean, with hot dry summers and mild and wet winters. This climate type is typical of the Aegean islands and the low-lying areas of central and southern Greece. The main feature that influences climate in Greece is Pindus mountain chain and its extension to Peloponnesus and Crete (Fig. 1) (European Academies Science Advisory Council (EASAC), 2010; Pnevmatikos and Katsoulis, 2006). To the west of Pindus a generally wetter climate is observed, whereas to the east of this mountain range the climate is much drier. Thus, precipitation in Greece is spatially variable, increasing from the east to the west but also from the south to the north. Annual precipitation in Western Greece amounts to >1000 mm/yr, while Eastern Greece along with the Aegean islands demonstrates considerably lower precipitation in the range of 400–600 mm/yr (Fig. 1a). Several microclimates can be observed, with mountain areas having an Alpine climate type, with harsh winters and cool summers. Temperate climate is present in the central and Northeastern part of the country. According to the Hellenic National Meteorological Service (http://www.hnms.gr), mean minimum air temperature in Greece is reported to range from 5 °C–10 °C near the coasts and 0 °C–5 °C over the mainland. Mean maximum air temperature ranges from 29 °C–35 °C.

Fig. 1a also shows the distribution of land uses in Greece, according to 2012 update of the EU CORINE (COoRdination of INformation on the Environment) (European Environmental Agency, 1995) inventory. Agricultural areas are mainly located in the eastern areas, whereas most forested areas are found in the central and western parts of the country. In southern regions and in Aegean islands, intense touristic development takes place during the last few decades, altering thus rapidly the existing land cover types. Fig. 1b shows the division of Greece into thirteen first-level administrative entities (excluding the autonomous monastic region of Mount Athos).

3. Results

Results of the analyses for annual and seasonal trends of daytime and nighttime LST are presented in Figs. 2–6. Areas colored with shades of blue show a decrease in LST, whilst those with red correspond to areas with an increasing trend.

3.1. Annual rate of LST change

Fig. 2a depicts the annual rate of change of daytime LST in Greece. A reduction in temperature is observed in the greater part of the country, while some increasing trends are observed in few coastal areas. Nevertheless, a general decrease in LST represents the main pattern observed for the annual daytime LST change. It is noticeable that the highest decreasing trends are found in areas occupied by mountains, like Pindus mountain range and Psiloritis Mountain in central Crete. Fig. 2b illustrates the rate of change in the average annual night temperature in Greece. An increase in temperature is observed all over the country, which in some areas is milder, while in some others it is more intense. A spatial pattern of the nighttime LST changes follows a northwest (lowest increases) to southeast (highest increases) distribution. This

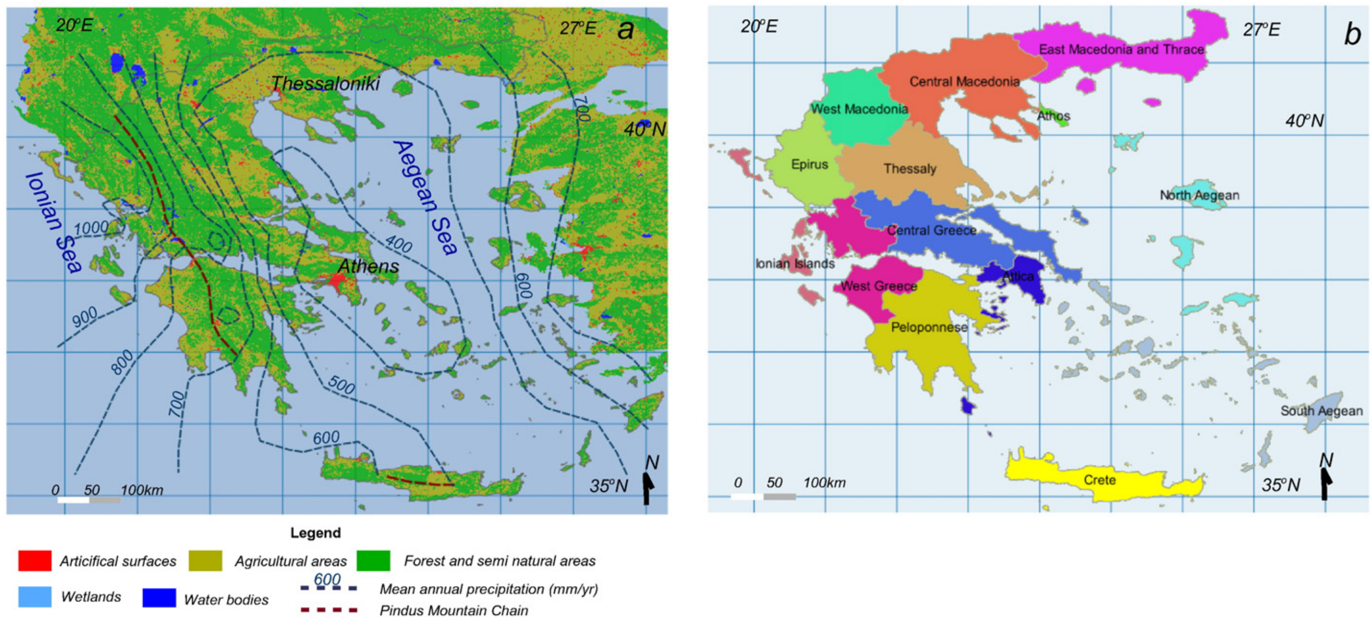

Fig. 1. a) The spatial distribution of annual precipitation and land uses in Greece. Precipitation data derived from 1961 to 1990 (Pnevmatikos and Katsoulis, 2006), land use data are obtained from CORINE Land Cover (CLC) 2012, Version 18.5.1 (European Environmental Agency, 1995) and b) administrative regions of Greece.

special pattern can be attributed to the dense forest that covers the NW part of the country, which provides a cooling effect in those areas.

3.2. Winter rate of LST change

Fig. 3a illustrates the change in the daytime winter LST for Greece. There is an increase in the daily temperature in the winter season, with peak in the NW Greece which is covered by dense forest. This spatial trend is potentially attributed to the diminishing aerial extent of snow cover during this season throughout the study period in this mountainous part of the country. Fig. 3b shows the general increasing trend of nighttime LST during winter, with more intense heating effects in northern and central Greece and much lower values in the islands. This spatial pattern may reflect the same trend of diminishing snow cover, also observed in winter daytime LST trends. Areas however covered by the large urban centers like Athens (central Greece) and Thessaloniki (Northern Greece) may also demonstrate the Urban Heat Island (UHI) effect, which has also been documented in previous works that used MODIS LST data, e.g. in China (Zhou et al., 2016). Winter nighttime LST corresponds to the minimum annual LST and our results indicate that as far as minimum LST is concerned a definite increase is observed all over Greece.

3.3. Spring rate of LST change

Fig. 4a demonstrates the rate of change of spring daytime LST. Most regions show a decrease in the daily temperature during spring, while a few coastal areas and islands in the south and east have an increase, considering however that the spatial resolution of 10 km × 10 km does not allow for safe conclusions to be drawn at very limited geographical areas. In this case as well, the cooling effect of forests in central and Northern Greece should be noticed. Fig. 4b refers to trends in spring nighttime LST. A general increasing trend is observed throughout the country with a few areas demonstrating slight decreases. Again the cooling effect of the forests in the NW parts is evident.

3.4. Summer rate of LST change

Fig. 5a illustrates the rate of change in summer daytime LST. Negative daytime LST trend is the dominating pattern all over the country, with the exception of some coastal areas. In particular, there is an increase in temperature in some coastal parts of Northern Greece and in the eastern continental areas (Thessaly in central Greece), as well as the southeastern part of Peloponnese, the Easternmost Crete and the Ionian Islands. It seems that the dense forest cover and the sparse population in mainland of Greece, especially in northwestern parts, i.e. Pindus mountain chain, offer a cooling effect during this season as well. Day summer temperature corresponds to the maximum annual temperature and it can therefore be concluded that as far as maximum LST is concerned, there is a decreasing trend. The increasing trend of maximum LST which is observed in some coastal parts is a potential consequence of the intense touristic development in those areas in combination with the extended fires during this season. Those two factors have altered rapidly the pre-existing land use pattern during the last two decades. Fig. 5b illustrates the rate of change in summer nighttime LST. A dominating positive trend is observed all over the country, with maximum values found in Northeastern Greece and minimum values in northwest parts, confirming once more the forest cooling effect in those areas.

3.5. Autumn rate of LST change

Daytime LST drop is the dominating trend in autumn, with sporadic coastal areas demonstrating rising trends (Fig. 6a) the same as in the case of daytime summer LST. Fig. 6b shows the spatial distribution of nighttime LST trends. An increasing trend is observed throughout Greece, with a somehow homogeneous spatial pattern.

4. Discussion

Table 1 shows average daytime and nighttime LST trends during 2000–2017 in the various administrative regions over Greece (Fig. 1b). Considering that the viewing time of MODIS corresponds to midday and midnight, it is safe to assume that the daytime and nighttime LSTs obtained from MODIS correspond to maximum and minimum daily surface temperature. Our results indicated a decreasing maximum daily LST. Minimum LST increases however, and this is in agreement with previous works which have found that surface warming over land is associated with relatively larger increase in daily minimum temperature rather than in maximum temperature (Easterling et al., 1997).

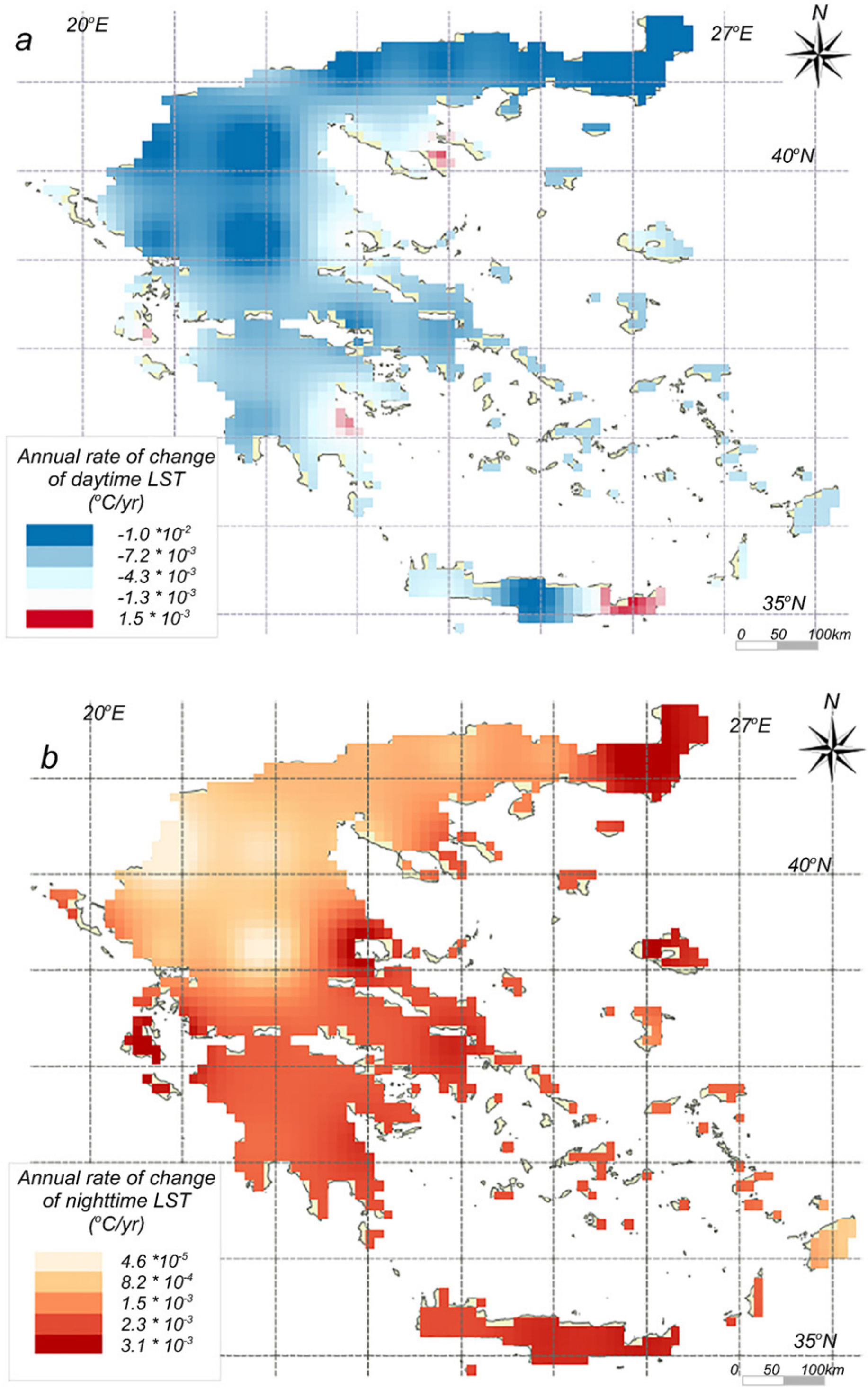

Fig. 2. Rate of change of annual a) daytime and b) nighttime LST during 2000–2017.

Quintana-Gomez (1999) conducted analyses of trends of maximum and minimum temperatures in Northern South America using ground station data and found a sustained increase of the minimum temperature and a diurnal temperature decrease in most stations analyzed during the last 25 years.

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Comparing daytime and nighttime trends on Table 1, one may notice that both annually and seasonally daytime LST decreasing trends are larger than the nighttime LST increasing trends. The only exception is winter where both daytime and night LST increase. It seems thus that in general the mean daily LST decreases, taking however into account the fact that estimating mean daily temperature as an average of the two extreme temperature observations, introduces a bias (Dall'Amico and Hornsteiner, 2006). An additional bias in computations comes from the fact that LST data are available for clear sky days only. Therefore any conclusion related to the trend of the mean daily LST should be drawn cautiously. There are however recent works that estimated mean surface temperature at the global scale using MODIS LST observations (Mao et al., 2017). In that work, during a twelve year period, i.e. 2001–2012, authors concluded that there cannot be a definite answer concerning global warming as although most regions in the Southern Hemisphere are warming, other regions e.g. central and eastern areas

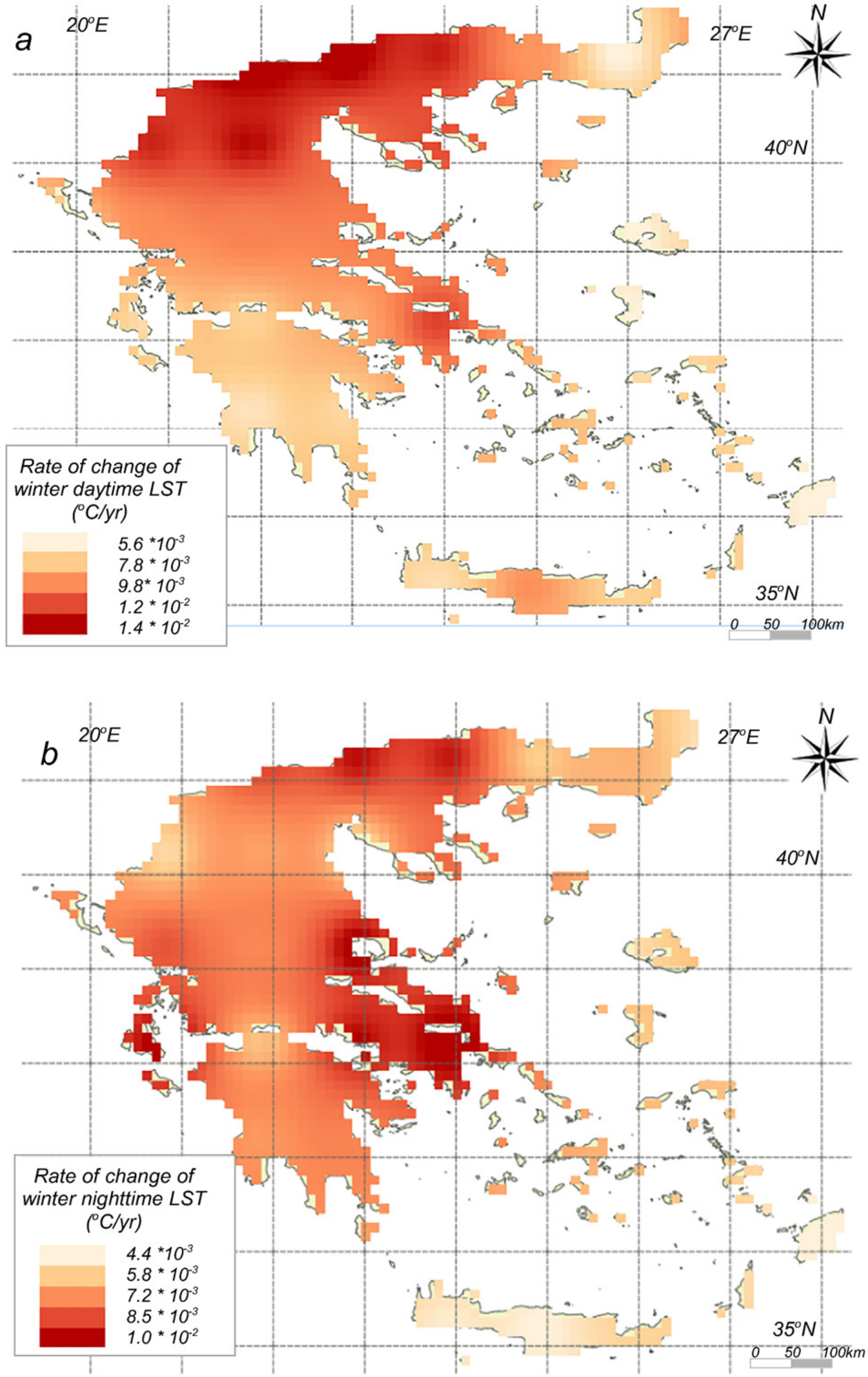

Fig. 3. Rate of change of winter a) daytime and b) nighttime LST during 2000–2017.

of Pacific Ocean, northern regions of the Atlantic Ocean, northern regions of China, Mongolia, southern regions of Russia, western regions of Canada and America, the eastern and northern regions of Australia, and the southern part of Africa are cooling.

Taking also into account that the annual maximum corresponds to summer daytime and accordingly the annual minimum corresponds to winter nighttime observations, some conclusions can be drawn related to the inter-annual LST variations, indicating a rise in minimum annual LST and a drop in maximum annual LST.

Another finding of the present work is the trend in diurnal LST range. As in most cases, i.e. annual and seasonal, the general observed LST trend is a decreasing daytime LST coupled with an increasing nighttime LST, it can be concluded that the diurnal LST range diminishes. Only during winter does this diurnal LST range seem not to have a unique trend. In winter a positive trend is observed for both daytime and nighttime LST, thus diurnal LST range is site specific and depends on the magnitude of change of LST in each area. Analogous results of diminishing diurnal LST were found elsewhere and were considered as important indicators of climate change (Qu et al., 2014). Sun et al. (2006) estimated diurnal skin temperature ranges based on satellite observations in the United States during 1996 to 2000. They found that diurnal temperature range is larger in bare, arid regions and the lowest range is found

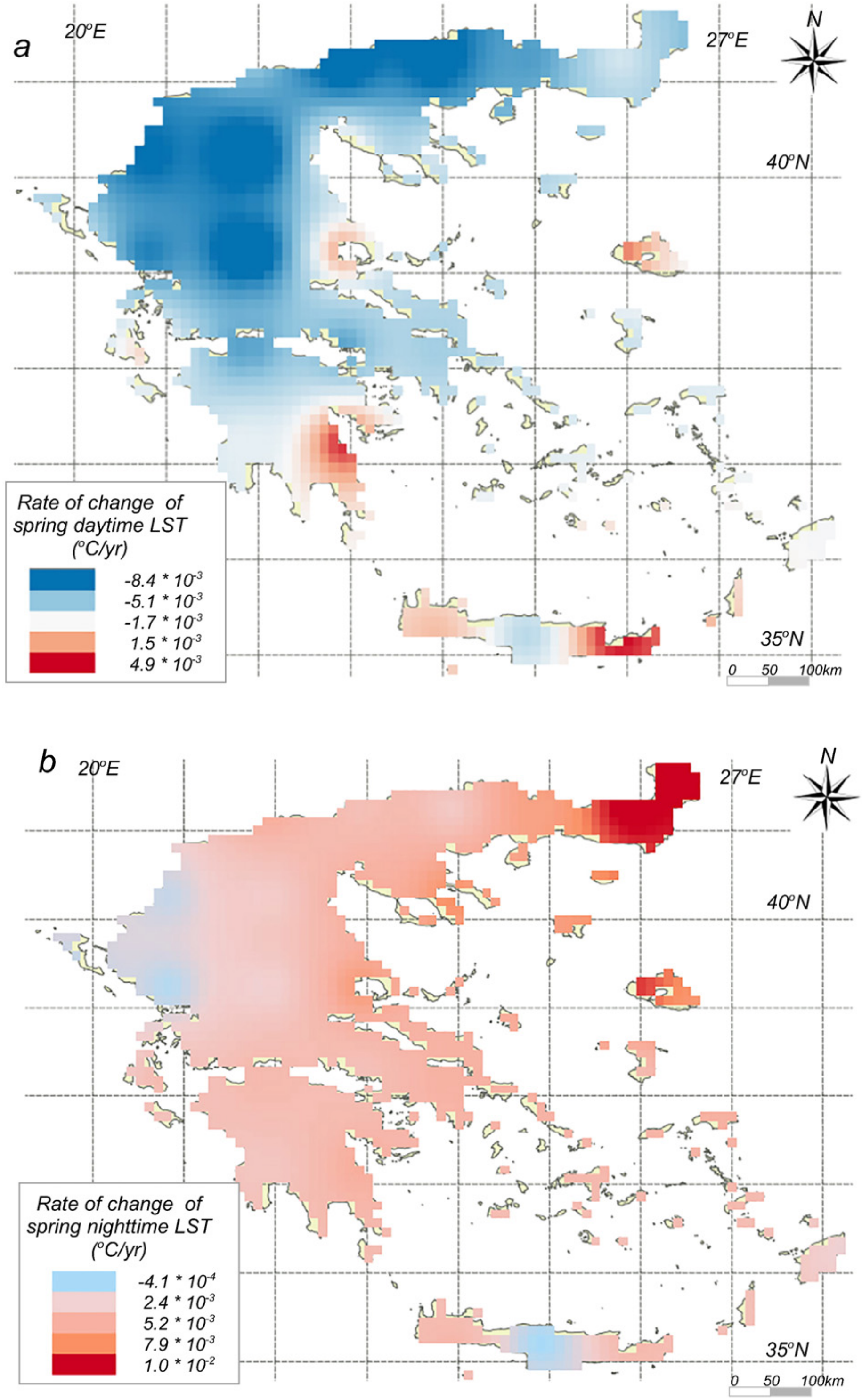

Fig. 4. Rate of change of spring a) daytime and b) nighttime LST during 2000–2017.

in urbanized areas. They concluded that satellite based estimates of diurnal temperature range are responsive to surface conditions and to climate change. Diminishing of diurnal temperature range is also found in China as an effect of Urban Heat Island (Zhou et al., 2016). Diurnal air temperature ranges were also evaluated for a 100-year period in the United States and a steady decreasing trend was also found, which was more significant in recent decades (Qu et al., 2014).

Limitations of the presented herein work are merely related to the general uncertainties of satellite observations, i.e. cloud cover, atmospheric conditions, topography, spatial resolution (Jin and Dickinson, 2010). Greece is a country with a unique landscape due to its diverse geography and its heterogeneous topography, including also its numerous islands. Therefore our results should be considered taking also into account that even the small spatial resolution of MODIS might pose large uncertainties in small geographical units like those of the small islands all over Aegean Sea. Thus, our finding for those areas should be examined cautiously. Additionally, although our work revealed a decrease in diurnal LST range which is an important indicator of climate change, as described above, the 17-year period of available data is not considered long enough so as to attribute safely the observed results

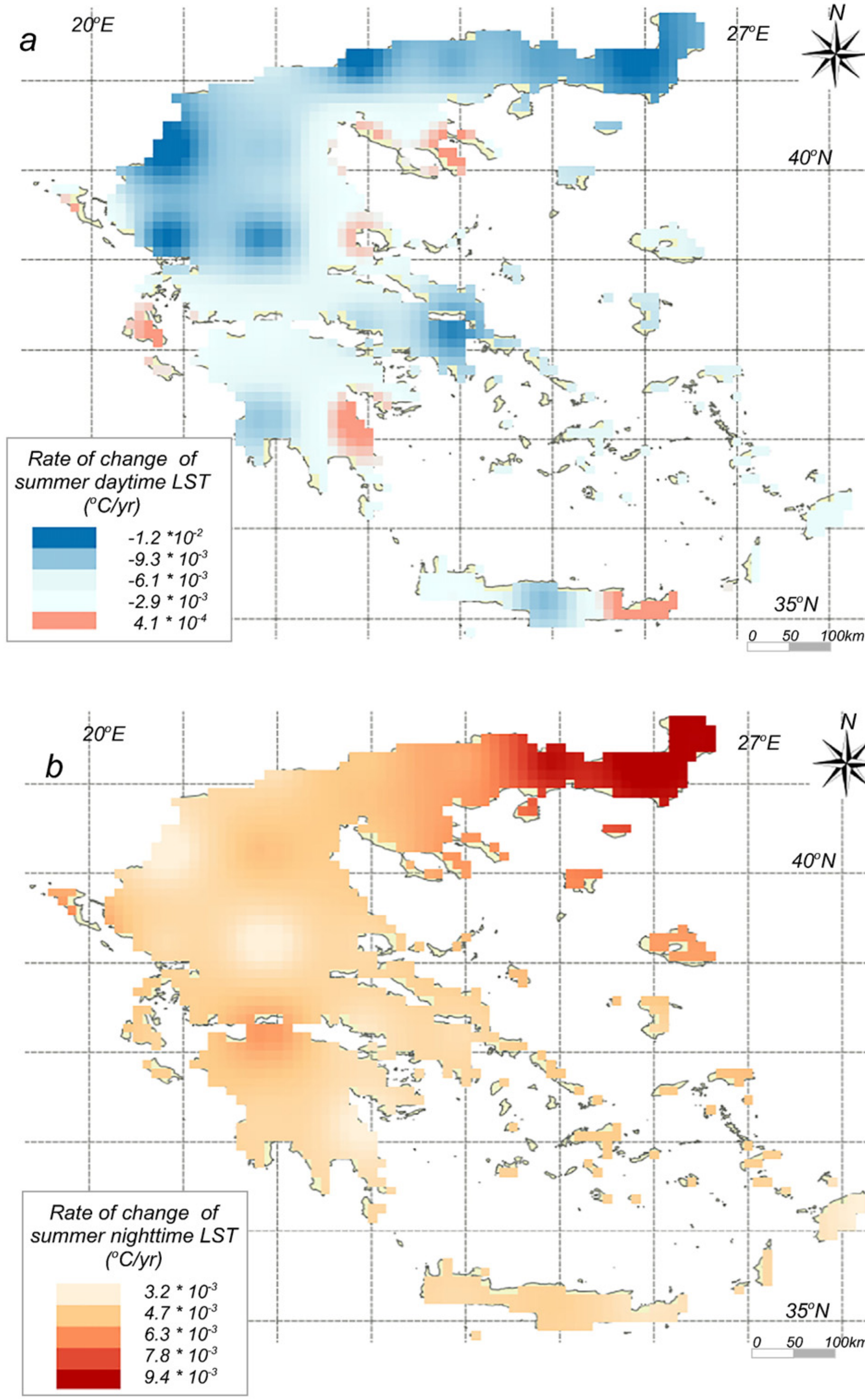

Fig. 5. Rate of change of summer a) daytime and b) nighttime LST during 2000–2017.

to climate change. Land uses and vegetation, soil types and soil moisture, topography are among factors known to influence LST observations. The exceptional role of land cover changes in both air temperature and LST is pointed out in Shen and Leptoukh (2011). Recent findings, concerning vegetation changes in Greece in 40 environmentally protected by the EU Natura 2000 network sites (http://ec.europa.eu/environment/nature/natura2000/index_en.htm), indicated that in all those areas, which correspond to minimum man intervention, a considerable greening pattern is observed with increased vegetation productivity, attributed to drivers related to climate changes such as increased CO_2 concentration and nitrogen deposition (Gemitzi and Angelou, 2017). It seems thus that there are potential evidences that would suggest that LST changes analyzed herein can be attributed to some important extent to the combined effect of vegetation and climate changes. We believe that increase of vegetation played a moderating role on LST and that LST changes would have been more severe in the absence of vegetation increase. Further research in needed however so as to elucidate the effects of other factors such as urban sprawl, precipitation changes, topography or soil types, in LST changes. It should also be taken into account that LST trends and diurnal variations presented here correspond to clear sky data only. It is a challenging task to incorporate both clear and cloudy sky data (Jin and Dickinson, 2010).

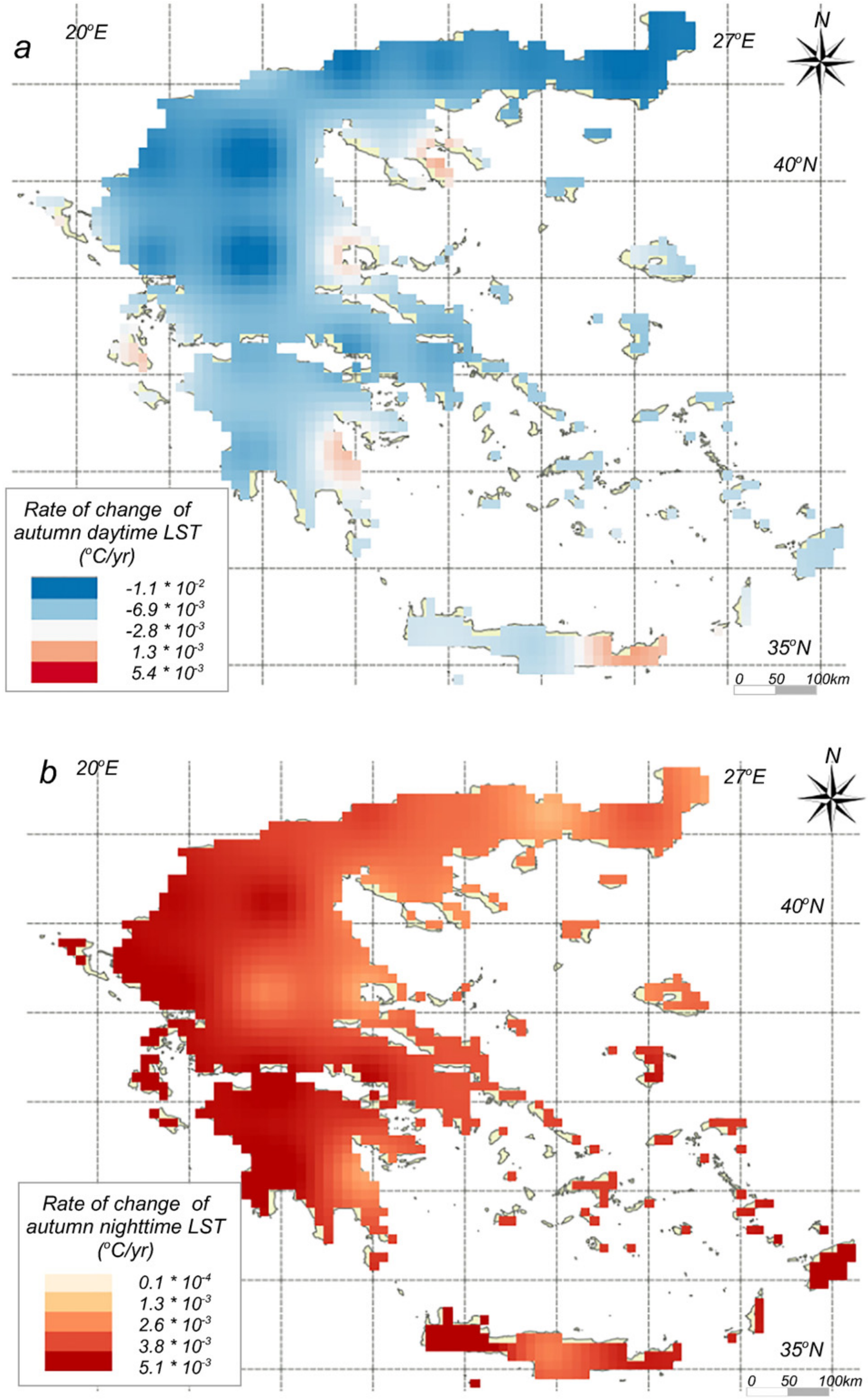

Fig. 6. Rate of change of autumn a) daytime and b) nighttime LST during 2000–2017.

Nevertheless, concerning climate change effects, as satellite data are obtained for clear sky conditions, they are considered as better indicators concerning diurnal temperature range, than surface air temperature based on station observations influenced by cloud effects (Sun et al., 2006).

5. Conclusions

Within the present work we analyzed the temporal and spatial variations of daytime and nighttime MODIS LST during 2000–2017, all over Greece, on both annual and seasonal basis. Results indicate that the annual trends of daily LST demonstrated a decrease in the most parts of Greece, with sporadic exceptions only at some coastal areas, where a slightly increasing trend was observed. Nighttime LST demonstrated increasing annual trends everywhere in Greece. Seasonal trends seem to follow the same pattern with a general daytime LST decrease and a definite increase in the nighttime LST. Furthermore, our study confirmed that the minimum annual LST has risen while the maximum annual LST showed a diminishing trend. Our findings also revealed that the diurnal LST range during the study period diminished in annual and seasonal terms, with an exception in some areas during winter.

Table 1
Trend of daytime and nighttime LST during 2000–2017 in the administrative regions of Greece.

Region	Slope of daytime LST trend line (°C/y)					Slope of nighttime LST trend line (°C/y)				
	Annual	Autumn	Spring	Summer	Winter	Annual	Autumn	Spring	Summer	Winter
North Aegean	−0.0041	−0.0040	−0.0012	−0.0044	0.0044	0.0015	0.0015	0.0045	0.0037	0.0041
South Aegean	−0.0032	−0.0030	−0.0011	−0.0028	0.0039	0.0010	0.0010	0.0021	0.0024	0.0029
Athos	−0.0064	−0.0073	−0.0055	−0.0068	0.0110	0.0009	0.0010	0.0041	0.0050	0.0078
Attica	−0.0063	−0.0062	−0.0033	−0.0073	0.0092	0.0021	0.0021	0.0041	0.0036	0.0083
Crete	−0.0053	−0.0032	−0.0005	−0.0042	0.0075	0.0023	0.0023	0.0022	0.0038	0.0044
Epirus	−0.0082	−0.0081	−0.0068	−0.0098	0.0103	0.0007	0.0007	0.0012	0.0040	0.0070
West Macedonia	−0.0095	−0.0095	−0.0083	−0.0092	0.0130	0.0005	0.0005	0.0028	0.0043	0.0069
Central Macedonia	−0.0071	−0.0071	−0.0063	−0.0066	0.0123	0.0011	0.0011	0.0043	0.0048	0.0075
East Macedonia & Thrace	−0.0094	−0.0094	−0.0056	−0.0100	0.0089	0.0020	0.0020	0.0073	0.0079	0.0065
Ionian Islands	−0.0019	−0.0019	−0.0017	−0.0011	0.0048	0.0016	0.0016	0.0017	0.0030	0.0054
Peloponnese	−0.0052	−0.0051	−0.0017	−0.0044	0.0071	0.0020	0.0020	0.0038	0.0038	0.0069
West Greece	−0.0067	−0.0067	−0.0050	−0.0052	0.0081	0.0019	0.0019	0.0035	0.0047	0.0072
Central Greece	−0.0071	−0.0070	−0.0049	−0.0067	0.0092	0.0017	0.0017	0.0039	0.0040	0.0080
Thessaly	−0.0073	−0.0073	−0.0059	−0.0066	0.0105	0.0011	0.0011	0.0037	0.0040	0.0076

While this national-scale study showed trends in daytime and nighttime LST, future work should focus on the role of various parameters on remotely sensed LST. Different land use / land cover patterns, soil moisture conditions, air temperature, precipitation, are factors known to be related to changes in LST. Quantification of those relationships will help towards a better understanding of processes affecting our climate and will offer precious information to land surface models both at regional, continental and global scale.

Within this work we highlighted the limitations and the advantages of using remotely sensed LST data for climate studies. Our findings suggest that climate change along with other factors such as vegetation, that need to be further studied, influenced LST in Greece, mainly in the form of minimum daily LST increase and a decrease in diurnal LST range. As Greece is a typical Mediterranean country our results might reflect the pattern of LST changes all over this area. To gain insight of the processes that control the temporal and spatial patterns in LST changes, further research is needed to verify and expand our findings in other Mediterranean countries and to different land uses and topographic conditions.

Our approach is certainly applicable to other areas all over the world and to different scales, i.e. from national to local studies, taking into consideration limitations discussed herein. Future works are expected to provide even better results as the time series of available data will become larger and new satellite missions are expected to provide products of better spectral and spatial resolution, diminishing thus the various limitations of remotely sensed observations.

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